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Modeling the Single-Helical Axis State in the Reversed-Field Pinch

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Abstract— **The classical paradigm of the reversed-field pinch as a chaotic plasma has been challenged in recent years by the observation of the high-confinement single-helical axis (SHAx) state in which the plasma spontaneously develops a helical core. A reconstruction of this state using a minimally constrained model that captures the self-organized nature of the SHAx state is presented.**

Index Terms— **Magnetic confinement, plasma simulation.**

THE recent observation of the single-helical axis (SHAx) state in reversed-field-pinch (RFP) experiments [2] represents a significant improvement in plasma confinement in these devices. In the SHAx state, the magnetic surfaces in the core of the plasma develop a helical deformation with a bean-shaped cross section. The formation of this SHAx state is associated with the formation of an electron transport barrier in the core of the plasma [2], and provides enhanced confinement. In contrast, the classical chaotic behavior of the RFP gives only the modest confinement and was thought to prevent fusion power development with the RFP. The SHAx state offers the possibility of sustained high-performance RFP plasmas and therefore understanding the origin and structure of the SHAx state is of key importance to further developing the RFP.

In RFX-mod, the transition to the SHAx state occurs as the plasma current is increased and a single dominant helical mode arises spontaneously [2]. As this mode saturates, it first forms a magnetic island, and then annihilates the original magnetic axis in a saddle-node bifurcation [3], forming a helical plasma column despite the axisymmetric plasma boundary.

We have developed a simple model [1] for the SHAx state that is able to capture the essential physics of the self-organized helical structure. The model is based on multiregion relaxed MHD (MRxMHD) and represents the plasma as two nested Taylor-relaxed regions separated by an ideal transport barrier. The existence of a transport barrier around the core of the plasma is confirmed experimentally [2], validating our approach.

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An important difference between our MRxMHD model and the ideal MHD model that is usually used in equilibrium modeling is that MRxMHD does not assume that the plasma is foliated by continuously nested magnetic flux surfaces. Our model allows for more complicated magnetic topologies, including islands and chaotic field regions as well as regions of continuously nested flux surfaces.

Fig. 1(a) illustrates a reconstruction of the SHAx state that demonstrates the ability of MRxMHD to handle very complex magnetic topologies. Inside the transport barrier, the magnetic field lines form continuously nested flux surfaces. However, just outside the transport barrier, the magnetic field is a chaotic sea of magnetic field lines interspersed with small magnetic islands. The magnetic field structure simplifies further toward the edge of the plasma, where it becomes dominated by nested flux surfaces and small magnetic islands. These complex topological structures are not driven by plasma boundary perturbations as the plasma boundary is perfectly axisymmetric. Instead, the complex structures visualized in Fig. 1(a) arise from the plasma self-organization process.

The bean shape of the SHAx state is clearly visible in Fig. 1(a) in the shape of the magnetic flux surfaces near the core of the plasma. The helical nature of the SHAx state causes this bean-shape structure to rotate in the poloidal plane as the toroidal angle of the cross section pictured in Fig. 1(a) is varied.

The Poincaré points in Fig. 1(a) have been colored according to the safety factor (q-profile) of the magnetic field lines, which is a measure of the average pitch angle of the field line. Within the chaotic region localized bands of color indicate the presence of weakly chaotic fields that may be able to contribute to plasma confinement. For example, near the edge of the chaotic field region, there is a localized band of light blue field lines that are weakly chaotic.

The color scale used for Fig. 1(a) represents only part of the variation of the safety factor over the plasma. The color scale was chosen to focus on the details of the structure of the magnetic field in the chaotic field region. The full safety-factor profile is illustrated in Fig. 1(b). The safety-factor is relatively flat through the core of the plasma, but changes sign near the edge of the plasma due to the toroidal field reversal at the plasma edge.

The results presented in this paper were computed using the stepped-pressure equilibrium code [4]. The results were visualized using the MATLAB software.

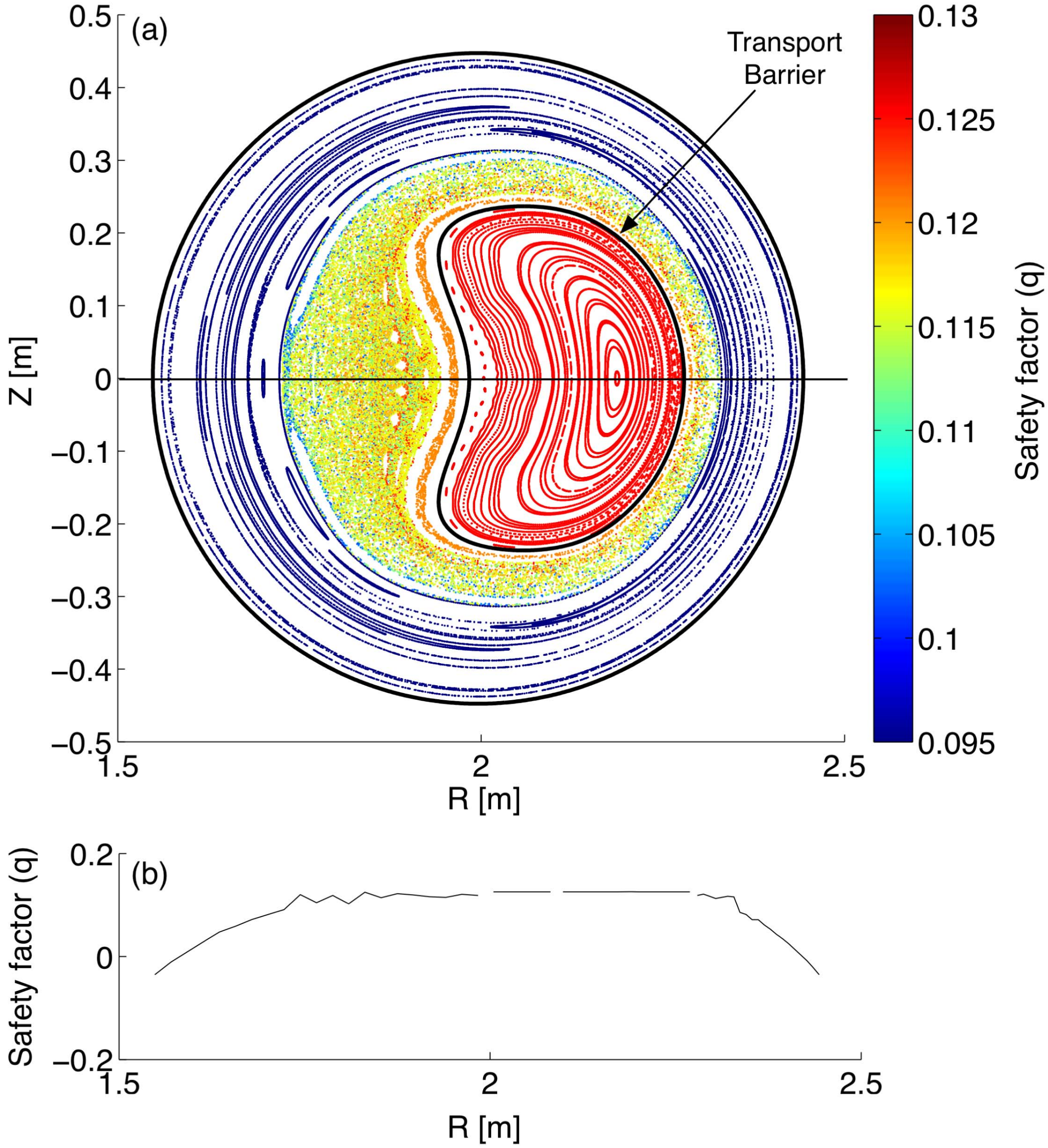

Fig. 1. (a) Poincaré section of the magnetic field lines of a MRxMHD model [1] of the RFP SHAx state [2]. The Poincaré points are colored according to the safety factor for that field line. The color scale has been chosen to highlight the structure in the chaotic field region. (b) Safety factor profile (q) computed through the $Z = 0$ midplane of the plasma.

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